

Hjj production: Signals and CP measurements

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Abstract

Higgs boson production in association with two tagging jets will be mediated by electroweak vector boson fusion and by gluon fusion. For the gluon fusion process, analysis of the azimuthal angle correlations of the two jets provides for a direct measurement of the CP-nature of the Htt Yukawa coupling which is responsible for the effective Hgg vertex.

HJJ PRODUCTION: SIGNALS AND CP MEASUREMENTS

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Higgs boson production in association with two tagging jets will be mediated by electroweak vector boson fusion and by gluon fusion. For the gluon fusion process, analysis of the azimuthal angle correlations of the two jets provides for a direct measurement of the CP-nature of the Htt Yukawa coupling which is responsible for the effective Hgg vertex.

1 Introduction

Higgs boson production in association with two jets has emerged as a promising channel for Higgs boson discovery and for the study of Higgs boson properties at the LHC. Interest has concentrated on vector-boson-fusion (VBF), i.e. the weak process $qq \rightarrow qqH$ which is mediated by t -channel exchange of a W or Z , with the Higgs boson being radiated off this weak boson. The VBF production cross section measures the strength of the WWH and ZZH couplings, which, at tree level, require a vacuum expectation value for the scalar field. Hence the VBF channel is a sensitive probe of the Higgs mechanism as the source of electroweak symmetry breaking.

Another prominent source of Hjj events are second order real emission corrections to the gluon fusion process. Such corrections were first considered in Ref. ^{1,2} in the large top mass limit and have subsequently been evaluated for arbitrary quark masses in the loops which induce the effective coupling of the Higgs boson to gluons.³ For a SM Higgs boson, the generic Hjj cross section from gluon fusion can somewhat exceed the VBF cross section of a few pb³ and, thus, gluon fusion induced Hjj events should also provide useful information on Higgs boson properties.

In this contribution we focus on the CP properties of the Higgs Yukawa coupling to the top quark, which is given by

$$\mathcal{L}_Y = y_t H \bar{t} t + i \tilde{y}_t A \bar{t} \gamma_5 t, \quad (1)$$

where H and A denote scalar and pseudo-scalar Higgs fields. Top quark loops then induce effective couplings of the Higgs boson to gluons which, for Higgs masses well below m_t , can be described by the effective Lagrangian ^{1,2}

$$\mathcal{L}_{\text{eff}} = \frac{y_t}{y_t^{SM}} \cdot \frac{\alpha_s}{12\pi v} \cdot H G_{\mu\nu}^a G^{a\mu\nu} + \frac{\tilde{y}_t}{y_t^{SM}} \cdot \frac{\alpha_s}{16\pi v} \cdot A G_{\mu\nu}^a G_{\rho\sigma}^a \varepsilon^{\mu\nu\rho\sigma}, \quad (2)$$

where $G_{\mu\nu}^a$ denotes the gluon field strength. From the effective Lagrangian emerge Hgg , $Hggg$ and also $Hgggg$ vertices, which correspond to triangle, box and pentagon top quark loops and which contribute to gluon fusion processes such as $qq \rightarrow qqH$, $qg \rightarrow qgH$ or $gg \rightarrow ggH$. One example for the first process and for the corresponding VBF diagram is shown in Fig. 1.

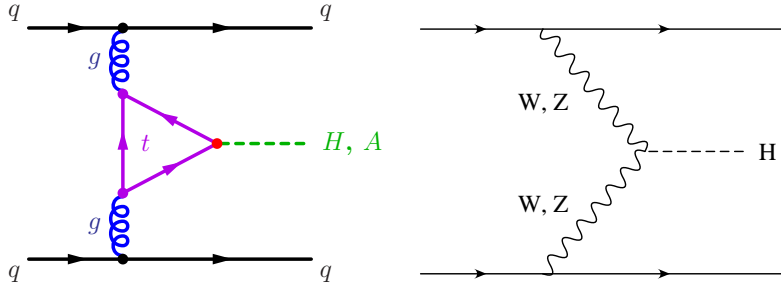


Figure 1: Quark scattering processes contributing to Hjj production via gluon fusion and vector boson fusion.

2 Azimuthal angle correlations

Analogous to the corresponding VBF case,^{4,5} the distribution of the azimuthal angle between the two jets in gluon fusion induced Hjj events can be used to determine the tensor structure of the effective Hgg vertex, which emerges from Eq.(2) as

$$T^{\mu\nu} = a_2 (q_1 \cdot q_2 g^{\mu\nu} - q_1^\nu q_2^\mu) + a_3 \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}, \quad (3)$$

with $a_2 = \frac{y_t}{y_t^{SM}} \cdot \frac{\alpha_s}{3\pi v}$ and $a_3 = -\frac{\tilde{y}_t}{y_t^{SM}} \cdot \frac{\alpha_s}{2\pi v}$. We assume SM-size couplings in our analysis below.

In resolving interference effects between the CP-even coupling a_2 and the CP-odd coupling a_3 it is important to measure the sign of the azimuthal angle between the jets. Naively one might assume that this sign cannot be defined unambiguously in pp collisions because an azimuthal angle switches sign when viewed along the opposite beam direction. However, in doing so, the “toward” and the “away” tagging jets also switch place, i.e. one should take into account the correlation of the tagging jets with the two distinct beam directions. Defining $\Delta\Phi_{jj}$ as the azimuthal angle of the “away” jet minus the azimuthal angle of the “toward” jet, a switch of the two beam directions leaves the sign of $\Delta\Phi_{jj}$ intact.⁵ The corresponding distributions, for two jets with

$$p_{Tj} > 30 \text{ GeV}, \quad |\eta_j| < 4.5, \quad |\eta_{j_1} - \eta_{j_2}| > 3.0, \quad (4)$$

are shown in Fig. 2 for three scenarios of CP-even and CP-odd Higgs couplings. All three cases are well distinguishable. The maxima in the distributions are directly connected to the size of the parameters a_2 and a_3 in Eq. (3). For

$$a_2 = a \cos \alpha, \quad a_3 = a \sin \alpha, \quad (5)$$

the positions of the maxima are at $\Delta\Phi_{jj} = \alpha$ and $\Delta\Phi_{jj} = \alpha \pm \pi$.

3 Observability at the LHC

The azimuthal angle correlations of the two leading jets in gluon fusion are fairly independent of the Higgs boson mass and they do not depend on the Higgs decay mode, except via kinematical effects due to cuts on the decay products. In order to observe them, however, background processes have to be suppressed by a sufficient degree. Clearly, this depends on which decay channels are available for the Higgs boson. The most promising case is a SM-like Higgs boson of mass around $m_H \approx 160 \text{ GeV}$ with decay $H \rightarrow W^+W^- \rightarrow l^+l^- \cancel{p}_T$ ($l = e, \mu$). We here give a brief summary of our findings. Details of the parton level simulation are given Ref.⁶ Similar to the analogous $H \rightarrow WW$ search in VBF,⁷ the dominant backgrounds arise from $t\bar{t}$ production in association with 0, 1, or 2 additional jets and from $WWjj$ production at order $\alpha^2\alpha_s^2$ (QCD $WWjj$ production) or at order α^4 (EW $WWjj$ production, which includes $H \rightarrow WW$ in VBF).

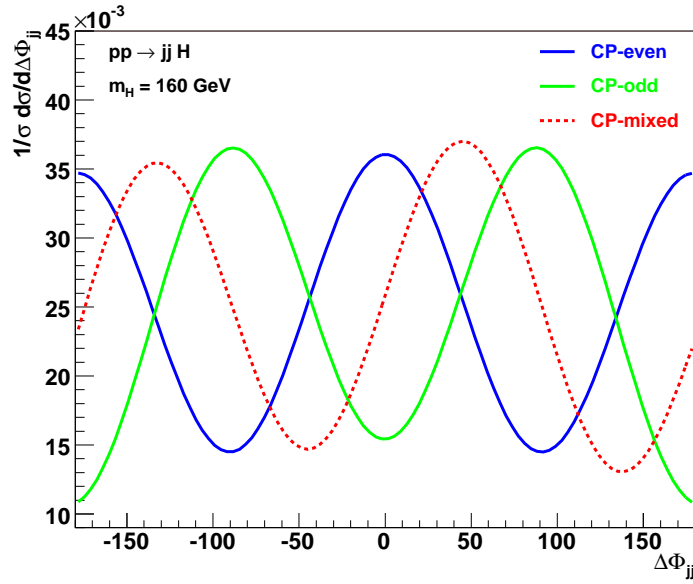


Figure 2: Normalized distributions of the jet-jet azimuthal angle difference as defined in the text. The curves are for the SM CP-even case ($a_3 = 0$), a pure CP-odd ($a_2 = 0$) and a CP-mixed case ($a_2 = a_3 \neq 0$).

Table 1: Signal and background cross sections and the expected number of events for $\mathcal{L}_{int} = 30 \text{ fb}^{-1}$ at different levels of cuts.

process	inclusive cuts	selection cuts		selection cuts & $\Delta\eta_{jj} > 3$	
	σ [fb]	σ [fb]	events / 30, fb^{-1}	σ [fb]	events / 30 fb^{-1}
GF $pp \rightarrow H + jj$	115	31.5	945	10.6	318
EW $pp \rightarrow W^+W^- + jj$	75	16.5	495	13.9	417
$pp \rightarrow t\bar{t}$	6830	23.3	699	1.5	45
$pp \rightarrow t\bar{t} + j$	9520	51.1	1530	13.4	402
$pp \rightarrow t\bar{t} + jj$	1680	11.2	336	3.8	114
QCD $pp \rightarrow W^+W^- + jj$	363	11.4	342	3.0	90
sum of backgrounds	18500	114	3410	35.6	1070

The first column of Table 1 gives the expected LHC cross sections for the fairly inclusive cuts of Eq. 4 (but $|\eta_{j1} - \eta_{j2}| > 1$) for the tagging jets, defined as the two highest p_T jets in an event, and lepton cuts given by

$$p_{T\ell} > 10 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad \Delta R_{j\ell} = \sqrt{(\eta_j - \eta_\ell)^2 + (\Phi_j - \Phi_\ell)^2} > 0.7. \quad (6)$$

The large top quark background can be suppressed by a veto on events with a b -quark tag on any observable jet. A characteristic feature of $H \rightarrow WW$ decay is the small angular separation and small invariant mass of the l^+l^- system,⁸ which is exploited by the cuts

$$\Delta R_{\ell\ell} < 1.1, \quad m_{\ell\ell} < 75 \text{ GeV}. \quad (7)$$

The signal is further enhanced by requiring large lepton transverse momentum, $p_{Tl} > 30 \text{ GeV}$, a transverse mass of the dilepton/missing E_T system consistent with the Higgs mass, $m_T^{WW} < m_H + 10 \text{ GeV}$ and not too small compared to the observed dilepton mass, $m_{\ell\ell} < 0.44 \cdot m_T^{WW}$, and a significant amount of missing p_T , $\cancel{p}_T > 30 \text{ GeV}$. The resulting cross sections and expected event rates for 30 fb^{-1} are given in the second and third columns of Table 1: with 30 fb^{-1} the

LHC can establish a Higgs signal in gluon fusion with a purely statistical error leading to a significance of $S/\sqrt{B} = 16$.

The resulting event sample of about 950 signal and 3400 background events is large enough and sufficiently pure to analyze the azimuthal angle between the two tagging jets. One finds, however, that the characteristic modulation of the $\Delta\phi_{jj}$ distribution in Fig. 2 is most pronounced for large rapidity separations of the tagging jets.⁶ Imposing $\Delta\eta_{jj} > 3$, one obtains the cross sections in the second to last column of Table 1 and azimuthal angle distributions as shown in Fig. 3 for an integrated luminosity of 300 fb^{-1} . Already for 30 fb^{-1} of data, however, can one distinguish the SM expectation in the left panel of Fig. 3 from the CP-odd case in the right panel with a purely statistical power of more than 5 sigma. We do not expect detector effects or higher order QCD corrections to substantially degrade these conclusions.

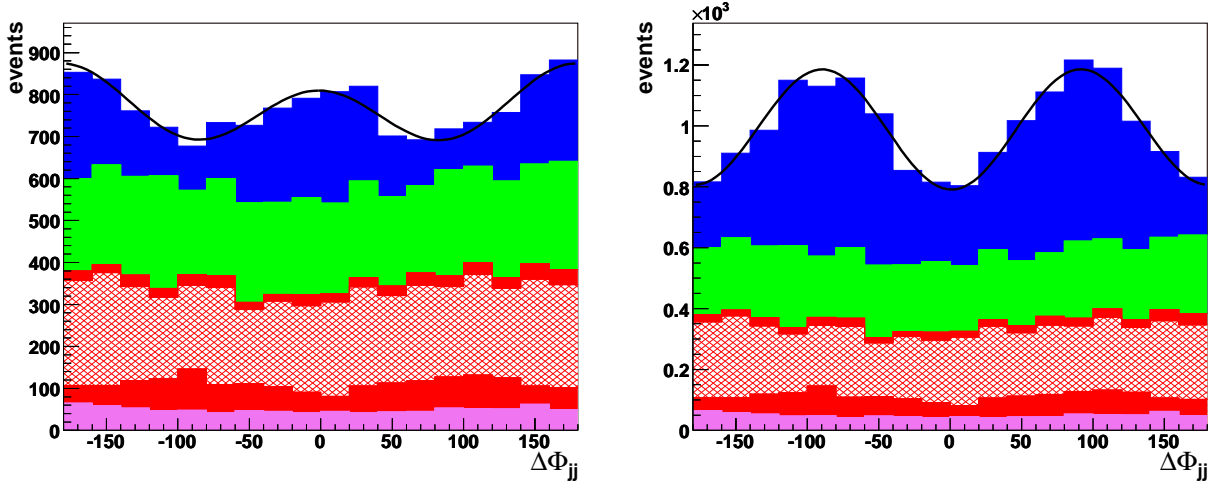


Figure 3: The $\Delta\Phi_{jj}$ distribution for a pure CP-even coupling (*left*) and a pure CP-odd coupling (*right*) for $\mathcal{L}_{int} = 300 \text{ fb}^{-1}$. From top to bottom: GF signal, EW W^+W^-jj , $t\bar{t}$, $t\bar{t}j$, $t\bar{t}jj$, and QCD W^+W^-jj backgrounds.

Acknowledgments

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